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Characterizing Fire Behavior from Laboratory Burns of Multi-Aged, Mixed-Conifer Masticated Fuels in the Western United States

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Abstract

Mastication is the process of chipping or shredding components of the tree canopy or above-ground vegetation to reduce the canopy, alter fire spread rates, and reduce crown fire potential. Mastication as a fuel treatment, either alone or in combination with prescribed fire, has been the subject of much research. This research has shown that modeling expected fire behavior in these fuels is challenging. Masticated materials from different ecosystems are unique and may react differently to fire. Therefore, there are no standard guidelines to help managers understand the potential fire behavior in treated areas. In this study, we evaluated burn characteristics for several mixed-conifer masticated fuels that range from 0 to 10 years since treatment. Overall, there was great variety in observed fire behavior, and time since treatment did not affect fire behavior characteristics. The method used to masticate fuel has some impact on burning, with larger pieces of fuel tending to act as a barrier to fire spread. From our limited experimental burns, fire behavior in the laboratory was best represented by the SB1 (low load activity fuels) fuel model. These results may not reflect how variations in fuel bed moisture and in situ environment would alter fire behavior characteristics in masticated fuels in management units.

Keywords: mastication, fire behavior modeling, BehavePlus

Cover photo: Masticated fuel from the Santa Fe National Forest, New Mexico, is burned under controlled conditions to characterize fire behavior.

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Disclaimer

Introduction

Mastication is the process of chipping or shredding components of the tree canopy or above-ground vegetation to reduce and protect against fire incursion into areas such as the wildland-urban interface (WUI). In recent years, mastication has gained popularity as a fuel treatment because it (1) effectively redistributes fuel from the tree canopy to the ground to reduce or eliminate the danger of fire in tree and shrub canopies (Battaglia et al. 2010); (2) may reduce detrimental effects on human health from smoke that occurs when prescribed burning is used to manipulate the fuel load (Naeher et al. 2006; Weinhold 2011); and (3) affects the probability of fire occurrence across landscapes by changing spread rates and reducing crowning behavior (Cochrane et al. 2012).

Mastication has been used either singly as a fuel treatment (Battaglia et al. 2010; Perchemlides et al. 2008; Wolk and Rocca 2009) or in conjunction with prescribed fire to reduce fuel (Bradley et al. 2006; Brewer et al. 2013; Keeley et al. 2013; Knapp et al. 2011; Kreye and Kobziar 2015; McIver et al. 2013; Reiner et al. 2009; Schwilk et al. 2009; Shakespear 2014; Southworth et al. 2011; Stottlemeyer et al. 2015). Most land management agencies leave masticated materials on the ground because it can provide other benefits such as improved nutrient cycling or wildlife habitat (Bradley et al. 2006). In addition, it can be difficult to burn a unit because of restrictions (e.g., smoke limits), limited windows for burning, and cost. However, prescribed fire, either alone or in conjunction with mastication, reduces surface fuel load in treatment areas making it a desirable treatment option (Brennan and Keeley 2015; McDaniel 2013).

The use of mastication alone as a fuel treatment for local fire-adapted vegetation communities has been examined by a number of researchers within the past few years (Kobziar et al. 2013; McIver et al. 2013; Schwilk et al. 2009). The arguments against a “mastication only” treatment range from vegetation losing its adaptation to fire in the absence of burning to prescribed fire treatments being necessary to produce the chemical or natural ecological effects required by a plant community (McIver et al. 2013). In some areas of the U.S., such as the southeast, mastication treatments must be revisited often because the shrub layer grows so rapidly after the treatment that it is rendered ineffective after as little as 2 years. Regrowth does not typically occur as quickly when mastication is followed by prescribed burning (Kobziar et al. 2013; Kreye et al. 2013; Kreye and Kobziar 2015).

Combining mastication treatments with prescribed fires can be problematic for managers for several reasons. Scheduling prescribed fires can be difficult once fuels have been masticated because of the narrow burn window available for burning such a fuel bed. Burning masticated sites increases in complexity when the treatments are within the WUI as there is potential for property damage should the fire escape (Bass et al. 2012; McDaniel 2013). It may be difficult to get approval to burn a management unit because of air quality regulations, leaving mastication alone as the only viable treatment option. Depending on weather and fuel conditions, prescribed fires may burn longer, and the depth of the flame zone may be greater. The resulting increase in consumption may lead to a higher total energy release, adversely affecting roots and underground vegetative structures, and thereby affecting regeneration (Agee and Skinner 2005; Perchemlides et al. 2008; Stottlemeyer et al. 2015).

Because masticated materials from different ecosystems may burn differently, there are no standard guidelines to help managers make decisions on whether or not to burn these materials. Fire behavior modeling is used to estimate the range of fire behavior that may occur in a treatment area. Anderson (1982) and Scott and Burgan (2005) developed standard fuel models to help managers estimate fire behavior in typical forest conditions, including activity fuels (e.g., slash). Masticated fuels form novel fuel beds, and standard fuel models may not represent the fire behavior seen in these fuel beds (Dickinson et al. 2013; Glitzenstein et al. 2006; Knapp et al. 2008, 2011; Kreye et al. 2012; Schiks and Wooten 2015) because of the changes to the 1-hr and 10-hr time lag fuels (e.g., fuel load and surface area-to-volume ratio) that are needed for modeling fire behavior (Rothermel 1972).

Several studies have attempted to use the fire behavior models described by Anderson (1982) and Scott and Burgan (2005) to predict fire behavior in masticated fuels. In California and southwest Oregon, Knapp et al. (2008) and Busse et al. (2005) tested burns in chaparral (*Arctostaphylos* and *Ceanothus* spp.). They concluded that, of the standard fuel models, Scott and Burgan's (2005) fuel models SB1 (low load activity fuels) and SB2 (moderate load activity fuels or low load blowdown) best predicted fire behavior for masticated materials in this vegetation type. In addition, masticated fuel beds from ponderosa pine (*Pinus ponderosa*), Kellogg oak (*Quercus kelloggii*), and chaparral (*Ceanothus* and *Arctostaphylos* spp.) were burned and the resulting fire behavior was compared to modeled results using a number of standard and custom fuel models, producing varying results (Knapp et al. 2011).

The purpose of this study was to characterize fire behavior for several types of mixed-conifer masticated fuels from four States across the western U.S. using materials that ranged in age from 0 to 10 years since treatment. Material from the sites was burned in a series of laboratory experiments to answer the following primary research questions.

1. What are the burn characteristics of the fuel beds produced by four different types of masticators?
2. How well do the standard or published custom fuel models describe the characteristics of these masticated burns?

Methods

Site Description

Masticated materials were collected from 15 mixed-conifer forests in Idaho, Colorado, New Mexico, and South Dakota (fig. 1; table 1). The masticated materials varied in age from 0 to 10 years since initial treatment. The treated areas were composed predominately of ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), western white pine (*Pinus monticola*), and western red cedar (*Thuja plicata*). At each site, 20 samples of masticated

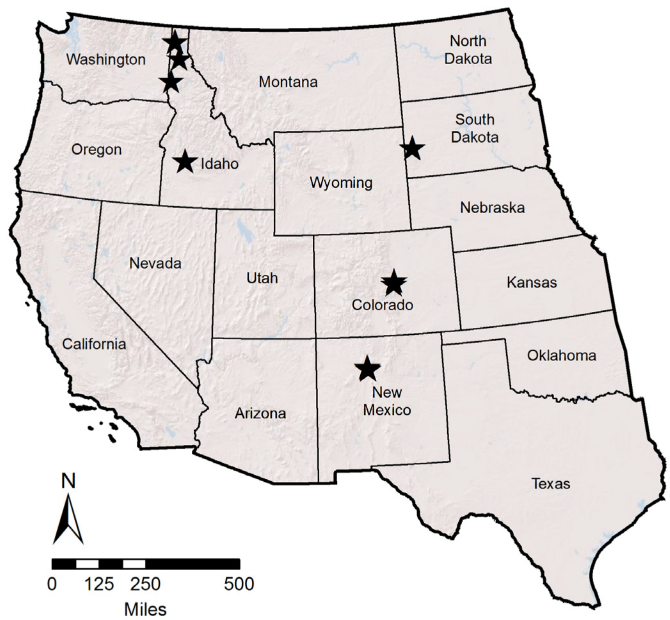

Figure 1—Masticated fuels were collected at 15 different sites in Idaho (6 sites), Colorado (3 sites), New Mexico (4 sites), and South Dakota (2 sites). See table 1 for site locations.

materials were collected for analysis using the destructive plot method of Hood and Wu (2006). Ten of these samples were used in the experimental burns. These samples were first separated in the laboratory into the standard 1-hr, 10-hr, and 100-hr size classes for particle characterization studies (Keane et al. 2018) and then recombined as described below for use in the experimental burns. More information on the experimental protocol can be found in Keane et al. (2018).

Fuel Bed Creation

Each fuel bed (fig. 2; table 2) was created on a burn platform consisting of an aluminum frame with wire mesh and removable heat-resistant 0.5 inch (1.27 cm) Thermal Ceramics Kaowool M Board (fig. 3). Experimental fuel beds were created using the relative proportions of 1-hr, 10-hr, and 100-hr woody fuels; wood chips (wood < 3mm thick); wood ribbons; litter; 1-hr and 10-hr bark; 100-hr bark; and bark ribbons from each masticated site (Keane et al. 2018). Because duff load does not contribute substantially to fire behavior at the flaming front, no duff from the sample locations was used in the experimental burn beds. The masticated material from the 10 sample plots was combined, and three fuel beds were created as representations of each study site. The amount of material selected in each fuel category was typically based on the mean fuel load for each fuel category from the field site. Occasionally, this mean seemed unreasonably high because of the variability in fuel deposition resulting from the mastication process itself, which resulted in uneven distribution of fuel across the site. In these rare cases, either the 50^{th} or 90^{th} percentile fuel load was used to more accurately represent the fuel load across the entire treatment site. Additionally, the fuel moisture content decreased during long-term storage at the lab. When weighing out fuels to create the burn beds, we adjusted fuel loading by size class accordingly.

Table 1—Location and treatment information for each of the masticated sites. Sites are sorted by age since time of treatment oldest to youngest.

Land management agency	Site code	Moisture regime	Dominant species	Mastication method	Treatment year	Time since mastication (yrs)
Boise Experimental Forest, Idaho	Amber	Dry	*Pinus ponderosa*	Rotating head	2004	10
Manitou Experimental Forest, Colorado	MEFChip	Dry	*Pinus ponderosa, Pseudotsuga menziesii, Symphoricarpos* sp., *Juniperus* sp.	Chipper	2004	10
Deception Creek Experimental Forest, northern Idaho	DC1	Moist	*Tsuga heterophylla, Pinus monticola, Larix occidentalis, Clintonia uniflora, Linnaea borealis*	Rotating head	2004	9
Manitou Experimental Forest, Colorado	MEFWS	Dry	*Pinus ponderosa, Pseudotsuga menziesii, Arctostaphylos uva-ursi*	Rotating head	2005	9
Santa Fe National Forest, New Mexico	LG	Dry	*Pinus ponderosa*, bunchgrass, *Fragaria* sp.	Horizontal drum head	2006	8
Priest River Experimental Forest, northern Idaho	PRCC1	Moist	*Pinus monticola, Tsuga heterophylla, Larix occidentalis, Clintonia uniflora*	Rotating head	2007	6
Valles Caldera National Preserve, New Mexico	VC1	Dry	*Pinus ponderosa, Carex* sp., *bunchgrass*	Horizontal drum head	2007-2008	6
Boise Experimental Forest, Idaho	AmberNew	Dry	*Pinus ponderosa, Pseudotsuga menziesii, Purshia tridentata, Symphoricarpos* sp.	Rotating head	2010	4
San Juan National Forest, Colorado	Skelton	Dry	*Pinus ponderosa, Pseudotsuga menziesii, Artemisia tridentata*	Rotating head	2010-2011	3
Black Hills Experimental Forest, South Dakota	BHMix	Dry	*Pinus ponderosa, Arctostaphylos uva-ursi*	Mower and whole tree yarding	2012	2
Black Hills Experimental Forest, South Dakota	BHMow	Dry	*Pinus ponderosa, Arctostaphylos uva-ursi, Symphoricarpos* sp.	Mower	2012	2
Santa Fe National Forest, New Mexico	PAL	Dry	*Pinus ponderosa, Carex* sp.	Horizontal drum head	2011-2012	2
Priest River Experimental Forest, northern Idaho	PR3	Moist	*Thuga plicata, Tsuga heterophylla, Pinus monticola, Larix occidentalis*	Horizontal drum head	2011	2
Valles Caldera National Preserve, New Mexico	VC2	Dry	*Pinus ponderosa*, bunchgrass, *Ribes* sp.	Horizontal drum head	2012	2
University of Idaho Experimental Forest, northern Idaho	UI	Moist	*Pinus ponderosa, Physocarpus malvaceus*	Horizontal head, boom mounted	2014	0

Figure 2—This sample fuel bed construction shows the masticated fuel prior to adding the excelsior and pine needles at the bottom of the bed for ignition.

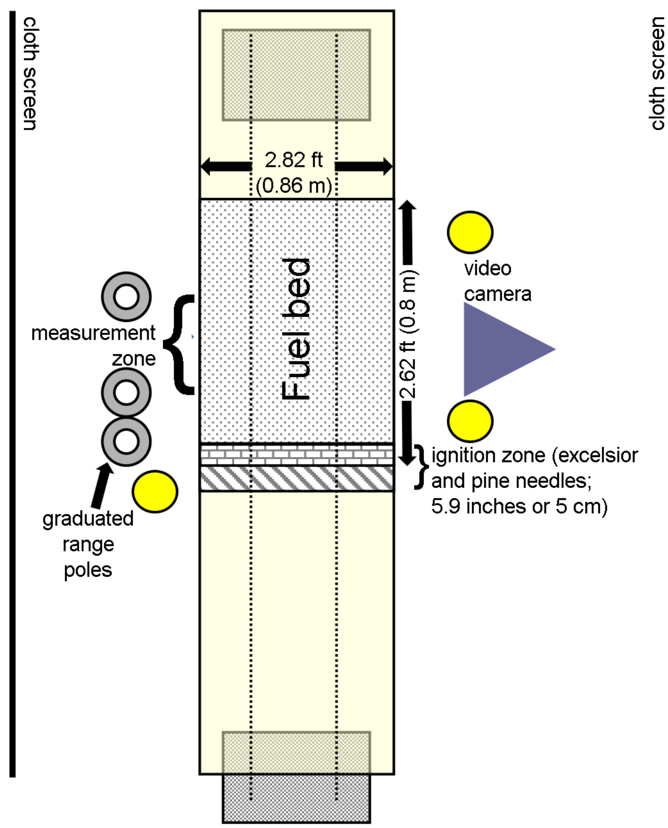

Figure 3—The burn platform consisted of a long bed with three graduated range poles on the left and a video camera on the right. Three halogen lights (yellow circles) simulated solar heating. The actual fuel bed was constructed within the dotted section of the platform. Two scales (dark grey rectangles) were used to collect data on the total mass lost as the bed burned. The slope of the bed was adjusted by raising one end of the fuel bed to the correct slope.

Fuel beds were conditioned in an environmental chamber at 95 ºF (35 ºC) and 3 percent humidity for at least 36 hours prior to burning to reduce moisture content as much as possible in all fuel categories. At the time of ignition, samples of 1-hr, 10-hr, and 100-hr fuels were collected and placed in a drying oven set to 212 ºF (100 ºC) for 72 hours. These fuel moisture measurements were used to determine the moisture

Table 2—The table below shows preburn conditions for moisture levels, slope of bed, fuel load, and bulk density for each site. Bulk density is computed for the total beds at each site then averaged for the number of microplots at each site. Fuel bed depth is for the masticated material only. SE = standard error. The sites are arranged from oldest to youngest in years since time of treatment.

Mastication age	Burn name	Slope	Fuel load 1-hr[a]	Fuel load 10-hr[b]	Fuel load 100-hr[c]	Total fuel load	Total oven-dry fuel load	Bulk density per site (Mean ± SE)	Fuel bed depth per site (mean ± SE)
yrs		*Percent*	*g m^-2^* $g\ m^{-2}$	$g\ m^{-2}$	$g\ m^{-2}$	$g\ m^{-2}$	$g\ m^{-2}$	$kg\ m^{-3}$	*cm*
10	Amber	12	1356.78	851.28	367.77	2575.82	2506.72	52.96 ± 6.98	1.7 ± 0.35
10	Amber	21	1456.41	742.86	430.77	2630.04	2524.72		
10	Amber	21	1463.00	755.31	375.09	2593.41	2480.74		
10	MEFChip[d]	21	1162.64	800.73	82.05	2045.42	1949.22	77.30 ± 6.00	1.8 ± 0.38
10	MEFChip	21	1165.57	800.73	83.52	2049.82	1951.98		
10	MEFChip	21	1164.10	800.73	82.05	2046.89	1983.04		
10	MEFChip	21	885.71	610.26	63.00	1558.97	1489.23		
9	DC1	12	1200.73	1584.62	2463.00	5249.82	5029.62	64.86 ± 12.80	4.4 ± 0.80
9	DC1	21	1188.28	1591.21	2470.33	5245.42	4925.02		
9	DC1	21	1195.60	1583.88	2465.93	5248.35	4930.74		
9	MEFWS	12	980.95	229.30	297.44	1507.69	1447.15	90.95 ± 12.70	1.4 ± 0.46
9	MEFWS	21	975.09	233.70	300.37	1509.16	1451.32		
9	MEFWS	21	978.02	230.77	290.11	1498.90	1449.22		
8	LG	12	753.48	1741.76	435.16	2926.01	2718.83	102.60 ± 13.16	2.0 ± 0.40
8	LG	21	749.08	1740.29	436.63	2927.47	2729.64		
8	LG	21	747.62	1741.76	438.10	2930.40	2722.95		
6	PRCC1	12	724.54	1424.91	823.44	2965.57	2761.43	72.49 ± 24.12	7.4 ± 2.08
6	PRCC1	21	724.54	1423.44	817.58	2964.10	2751.89		
6	PRCC1	21	724.54	1423.44	816.12	2972.89	2755.41		
6	VC1	12	1973.63	2338.46	1522.34	5834.43	5368.44	93.85 ± 6.93	3.3 ± 0.57
6	VC1	21	1973.63	2338.46	1522.34	5834.43	5475.41		
6	VC1	21	1973.63	2338.46	1525.27	5837.36	5485.51		

Table 2—Continued.

Mastication age	Burn name	Slope	Fuel load 1-hr[a]	10-hr[b]	100-hr[c]	Total fuel load	Total oven-dry fuel load	Bulk density per site (Mean ± SE)	Fuel bed depth per site (mean ± SE)
yrs		*Percent*	*g m^-2^*	*g m^-2^*	*g m^-2^*	*g m^-2^*	*g m^-2^*	*kg m^-3^*	*cm*
4	AmberNew	12	2099.63	1421.25	1164.84	4783.88	4514.13	52.30 ± 5.49	3.1 ± 0.66
4	AmberNew	21	2184.62	1444.69	1154.58	5194.14	4934.04		
4	AmberNew	21	2348.72	1454.95	1390.48	4685.71	4626.99		
3	Skelton	12	1650.55	913.55	216.85	2773.26	2690.64	79.39 ± 13.95	2.6 ± 0.84
3	Skelton	21	1641.39	912.09	219.78	2766.96	2679.25		
3	Skelton	21	1643.88	904.76	218.32	2780.95	2664.42		
2	PR3	12	1050.55	962.64	512.82	2527.47	2372.57	70.53 ± 12.81	3.6 ± 1.50
2	PR3	21	1053.48	968.50	505.49	2534.80	2368.60		
2	PR3	21	1057.88	964.10	512.82	2526.01	2350.85		
2	BHMix[d]	21	2027.84	369.23	104.03	2501.10	2349.12	75.34 ± 7.32	0.7 ± 0.17
2	BHMix	21	2027.84	367.77	104.03	2499.63	2279.79		
2	BHMix	21	2030.04	369.96	104.03	2504.03	2446.13		
2	BHMow	12	1144.32	246.15	70.33	1460.81	1374.84	65.70 ± 8.49	1.0 ± 0.31
2	BHMow	21	1148.72	246.15	76.19	1471.06	1365.59		
2	BHMow	21	1147.25	246.15	74.73	1468.13	1424.84		
2	BHMow	21	1147.25	246.15	67.40	1460.81	1390.39		
2	PAL	12	1570.70	1986.81	316.48	3871.06	3610.44	101.55 ± 10.72	2.7 ± 0.93
2	PAL	21	1570.70	1986.81	313.55	3872.53	3610.12		
2	PAL	21	1570.70	1986.81	315.02	3873.99	3582.63		
2	VC2	12	1518.68	780.22	1049.08	3347.99	3164.76	90.40 ± 10.26	2.9 ± 0.90
2	VC2	21	1521.61	781.68	1030.04	3333.33	3184.59		
2	VC2	21	1518.68	783.15	1030.04	3331.87	3145.14		
0	UI[e]	21	1410.30	973.63	610.99	2994.87	2820.99	N/A	N/A

[a] -hr fuels include 1h woody particles, wood chip litter, wood ribbons, 25% of the 1-10-hr bark category, and the fresh litter (dried pine needles, grass, dried leaves and roots, pine cones, and more).
[b] 10-hr fuels include 10h woody particles and 75% of the 1-10-hr bark category.
[c] 100-hr fuels include 100h woody particles and the 100-hr bark.
[d] All of the beds at this site were burned at the higher slope in an attempt to get the fire to spread.
[e] Only one fuel bed was built from materials received from a University of Idaho mastication study site. More information on this site can be found in the paper by Lyon et al. (submitted).

content of each fuel category, as well as the oven-dry weight for the fuel load needed in fire behavior modeling (table 2).

Experimental Burns

Experiments were conducted at the U.S. Forest Service's combustion facility at the Missoula, Montana, Fire Sciences Laboratory. The combustion facility is a large, environmentally controlled chamber. Additional information on the combustion facility may be found in Christian et al. (2004). During the experiments, air temperature in the burn chamber was approximately 69.8 °F (21 °C). Relative humidity was not controlled and approximated that of the outside ambient air. The burn chamber does not include the ability to adjust wind speed, and the burns had the potential to be too intense to burn in the wind tunnel. Therefore, wind speed was not explicitly factored into the experiments.

The fuel bed was inclined at either 11.75 (low) or 21.25 (moderate) percent slope. Graduated range poles were placed at 0.5, 1.0, and 2.0 ft (0.15, 0.30, 0.61 m) along the fuel bed. Each burn was filmed using a GoPro Hero 3+ Silver Edition HD video camera. Cloth screens were set up on each side of the burn platform to block air flow during the experimental burn. The screens also aided in blocking any light from interfering with the video.

Two halogen work lights on either side of the video camera tripod (fig. 4) were focused on the material in an effort to preheat the air above the fuel and facilitate burning to simulate solar heating. A third light was placed on the opposite side of

Figure 4—The actual burn bed configuration consisted of the burn platform, graduated range bars, halogen lights, and a video camera. Notice the excelsior and pine needles at the bottom of the photo that were used to ignite the fuel bed.

the fuel bed over a layer of shredded aspen wood (excelsior) used for igniting the experimental burn beds. This third light was turned off at the time of ignition since it interfered with the video recording.

All of the fires were ignited from a line of excelsior and pine needles (5.9 inches; 15 cm wide) at the beginning of the fuel bed (fig. 3). The material was ignited with a single pass at the bottom edge of the excelsior mix using a handheld butane torch. Rate of spread was calculated as the amount of time it took the fire to travel the 1-ft distance between the 2^{nd} and 3^{rd} graduated poles in the measurement zone (fig. 3). Flame height was recorded using the height measures on the graduated poles. Both minimum and maximum flame heights were recorded for each burn. Consistency of the flaming front was first measured visually and later verified using the video from each burn.

We tested for statistical relationships between time since mastication and fire behavior using the Kendall tau (K_τ) statistical method, which is a nonparametric rank-correlation measure that estimates and assesses the strength of the relationship between fire behavior and time since mastication. With this metric we do not assume a cause-and-effect; we only test for a relationship between time since mastication and fire behavior. All experimental beds were used in the analyses.

Fire Behavior Modeling

Surface fire behavior was estimated using BehavePlus version 5.0.5. Predicted surface fire rate of spread was obtained using Rothermel's fire spread model (Albini 1976; Rothermel 1972), while flame length was estimated using Byram's (1959) equation. Moisture values were calculated from samples collected and oven-dried at the start of each burn; values are summarized in table 3. Surface fire behavior rate of spread and flame length from our experimental burns were compared to three standard and five custom fuel models (table 4) (Anderson 1982; Glitzenstein et al. 2006; Knapp et al. 2011; Scott and Burgan 2005). The three standard fuel models were 11 (light logging slash), SB1 (low load activity fuel), and SB2 (moderate load activity or low load blowdown) (Anderson 1982; Scott and Burgan 2005). These three fuel models were the most representative of the 53 standard fuel models given the fuel loads measured for the experimental sites. Custom fuel models for masticated fuel have been developed by Knapp et al. (2011) for California chaparral and by Glitzenstein et al. (2006) for pine forests in the southern U.S. These custom fuel models were also compared to the experimental burns since they were designed specifically for masticated fuel.

Table 3—Fuel moisture values for 1-hr, 10-hr, and 100-hr fuel classes were measured during the experimental burns.

Fuel moisture	Minimum	Average	Maximum
	---------------------*percent*---------------------		
1-hr fuel	3	5	8
10-hr fuel	2	5	7
100-hr fuel	2	5	8
Live woody fuel	150	150	150

Table 4—Standard and published custom fuel model characteristics were used in fire behavior simulation. A dash represents a value that was not needed in a given fuel model.

		Standard fuel models			Knapp et al. (2011)			Glitzenstein et al. (2006)	
		11	SB1	SB2	Low load[a]	Moderate load[a]	High load[a]	Transect, shallow[b]	Transect, deep[b]
1-hr fuel load	Mg ha^{-1}	0	3.36	10.09	7.8	12.7	17.6	8.31	8.31
10-hr fuel load	Mg ha^{-1}	0	6.73	9.53	5.5	13.3	29.4	24.1	24.1
100-hr fuel load	Mg ha^{-1}	0	24.66	8.97	0.7	2.8	13.1	35.15	35.15
Live herbaceous fuel load	Mg ha^{-1}	0	0	0	0	0	0	0	0
Live woody fuel load	Mg ha^{-1}	0	0	0	0	0	0	0.95	0.95
1-hr surface area-to-volume ratio	m^2 m^{-3}	4921	6562	6562	2461	2461	2461	6562	6562
Live woody surface area-to-volume ratio	m^2 m^{-3}	—	—	—	—	—	—	5249	5249
Fuel bed depth	m	0.30	0.30	0.30	0.11	0.16	0.27	0.05	0.30
Dead fuel moisture of extinction	percent	15	25	25	25	25	25	25	25
Dead fuel heat content	kJ kg^{-1}	18622	18622	18622	18622	18622	18622	18622	18622
Live fuel heat content	kJ kg^{-1}	—	—	—	—	—	—	18622	18622

[a] Knapp et al. (2011) developed custom fuel models for sites in California that were initialized with standard model SB2 for three levels of loading.

[b] Glitzenstein et al. (2006) developed a custom fuel model for sites in South Carolina that were initialized with standard fuel model SB3 and used two different fuel bed depths.

We compared the results of the modeling effort to observed values from the experimental burns. While we recorded measured values of flame height and modeled estimates of flame length, the two are quite similar in this instance. Since the experiment did not include wind and the slopes were relatively low, the resulting flames were nearly vertical, so that flame height could be used as a proxy of flame length in these experiments.

Results

Experimental Burns

Fires That Did Not Burn Completely

In 16 of the 45 experimental fires, the fuel bed did not burn completely (fig. 5), and we were unable to calculate a rate of spread in the measurement zone (fig. 3). These beds exhibited smoldering fire behavior, which cannot be calculated using Rothermel's (1972) fire spread model. All 10 of the fuel beds containing fuels masticated using a mower or chipper exhibited smoldering fire behavior. Most failed to burn the entire fuel bed as there was very little fuel (fuel bed depth) to facilitate fire spread.

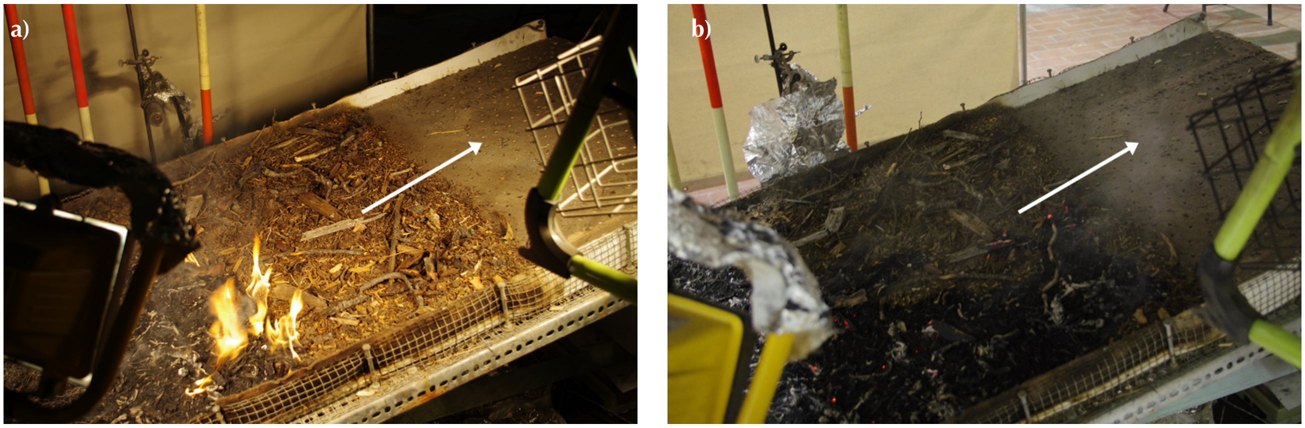

Figure 5—This fuel bed from the Black Hills Experimental Forest, South Dakota (BHMix) showing fire behavior during the flaming (a) and smoldering (b) phases, is typical of burns that did not completely burn the fuel bed, with the fire stopping about halfway. The gray ash at the beginning of the burn is the excelsior used to ignite the fuel bed. Arrows indicate upslope.

Fires That Did Not Burn Homogeneously

An additional 11 burns either failed to burn the entire fuel bed or exhibited strong effects from interactions with the sides of the fuel bed. Two different behaviors were observed. In some cases, the center of the bed burned more quickly than the edges (fig. 6). In other cases, one side burned to the end of the bed before the other (fig. 7). The remainder of the fuel bed then burned primarily through flanking fire (fig. 7). In most of these experiments, we were unable to obtain reliable estimates of either flanking fire rate of spread or head fire rate of spread in the measurement zone.

Fires That Burned Completely and Homogeneously

The remaining 18 burns demonstrated fairly steady progression with sustained burning rates throughout the experiment. We were, therefore, able to calculate a rate of spread and flame length across the measurement zone for further analysis. Fire behavior was minimal in all of these burns, and there was no measurable difference

Figure 6—This fuel bed from the Priest River Experimental Forest, in northern Idaho (PRCC) during (a) and after (b) the burn, is typical of fires that exhibited edge effects. In this example, the flaming front at the center of the bed is 1 ft (0.3 m) ahead of that at the edges. The fire then burned to the end of the fuel bed through a combination of flanking and head fires. Arrows indicate upslope.

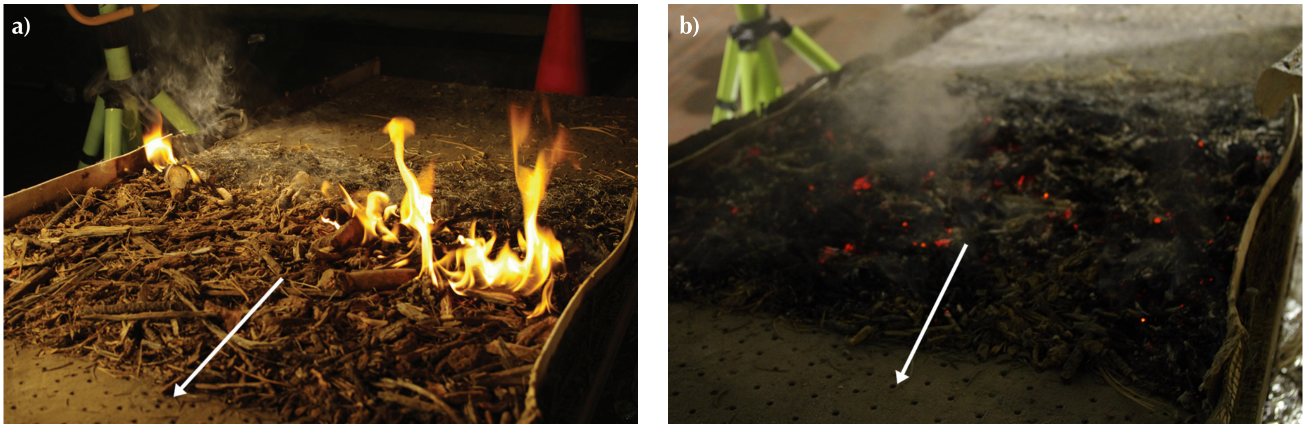

Figure 7—This fuel bed from the Santa Fe National Forest, New Mexico (PAL), showing fire behavior during the flaming (a) and smoldering (b) phases, is typical of burns that exhibited flanking fire. This flanking fire was responsible for burning the entire fuel bed. Arrows indicate upslope.

in fire behavior among sites (table 5, fig. 8). Rate of spread at all sites was less than 1.0 ft/min (0.3 m/min), with an average of 0.3 ± 0.2 ft/min (0.1 ± 0.06 m/min). Flame heights ranged from 0.25 ft to 3.0 ft (0.08 m to 0.91 m). Average minimum flame height was 0.5 ± 0.2 ft (0.2 ± 0.06 m), while average maximum flame height was 1.4 ± 0.8 ft (0.4 ± 0.2 m). Behind the flaming front, flames typically died out in less than 30 minutes (table 5), while smoldering may have continued for significantly longer (data not shown). The two fuel beds with the longest flame duration across the fuel bed (VC1 and PAL) contained a mix of fuels from all fuel load categories.

Statistical Relationships

We tested all of the experimental burns to determine if there was a relationship between the age of the fuel and fire behavior (table 5; see also Sikkink et al. 2017). Statistical analysis reveals that there was no relationship between time since mastication and any of the following parameters: fuel load (Kτ = 0.009; P = 0.94), maximum flame length (Kτ = 0.014; P = 0.90), or surface rate of spread (K_τ = 0.020; P = 0.93).

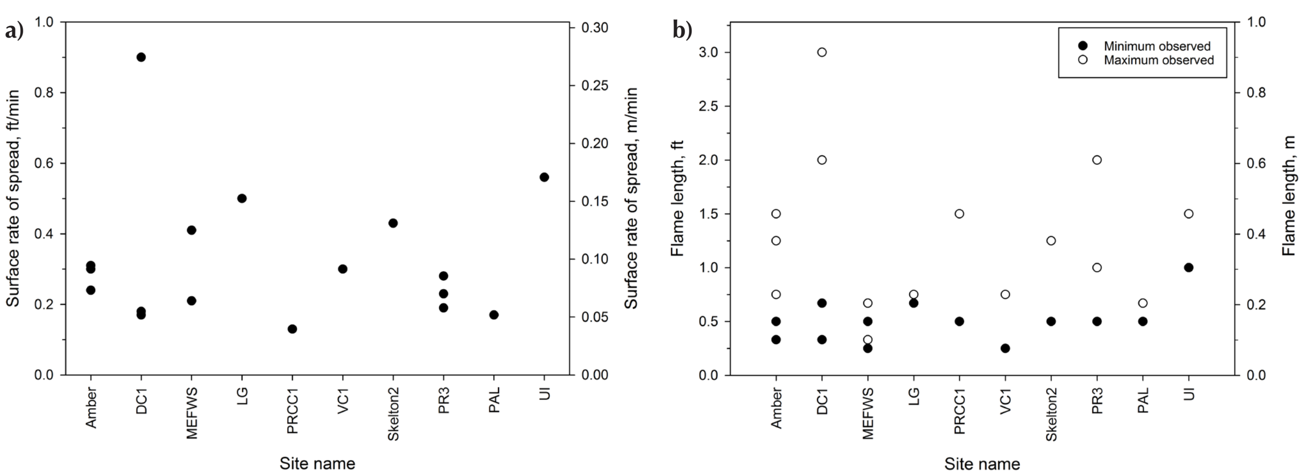

Figure 8—These observed rates of spread and flame lengths for the 18 burns demonstrate that overall rates of spread (a) were low, and flame lengths (b) were fairly small.

Table 5—Observed fire behavior is shown for the 18 burns that demonstrated steady and sustained burning. Site codes are listed in table 1.

Time since mastication	Burn name	Slope	Rate of spread		Min flame height		Max flame height		Flaming duration
years		*percent*	*ft/min*	*km/hr*	*ft*	*m*	*ft*	*m*	*min:sec*
10	Amber	12	0.30	0.005	0.50	0.15	0.75	0.23	21:33
		21	0.31	0.006	0.75	0.23	1.50	0.46	23:00
		21	0.24	0.004	0.33	0.10	1.25	0.38	24:10
9	DC1	12	0.90	0.016	0.33	0.10	2.00	0.61	26:16
		21	0.18	0.003	0.67	0.20	3.00	0.91	26:53
		21	0.17	0.003	0.33	0.10	3.00	0.91	26:09
9	MEFWS	12	0.21	0.004	0.25	0.08	0.33	0.10	16:22
		21	0.41	0.008	0.33	0.10	0.67	0.20	26:10
		21	0.41	0.008	0.50	0.15	0.67	0.20	19:01
8	LG	21	0.50	0.009	0.67	0.20	0.75	0.23	19:20
6	PRCC1	21	0.13	0.002	0.50	0.15	1.50	0.46	27:37
6	VC1	21	0.30	0.005	0.25	0.08	0.75	0.23	39:01
3	Skelton	21	0.43	0.008	0.50	0.15	1.25	0.38	18:25
2	PR3	12	0.23	0.004	0.50	0.15	1.00	0.31	18:06
		21	0.28	0.005	0.50	0.15	2.00	0.61	26:53
		21	0.19	0.003	0.50	0.15	2.00	0.61	19:32
2	PAL	21	0.17	0.003	0.50	0.15	0.67	0.20	40:53
0	UI	21	0.56	0.010	1.00	0.31	1.50	0.46	27:10

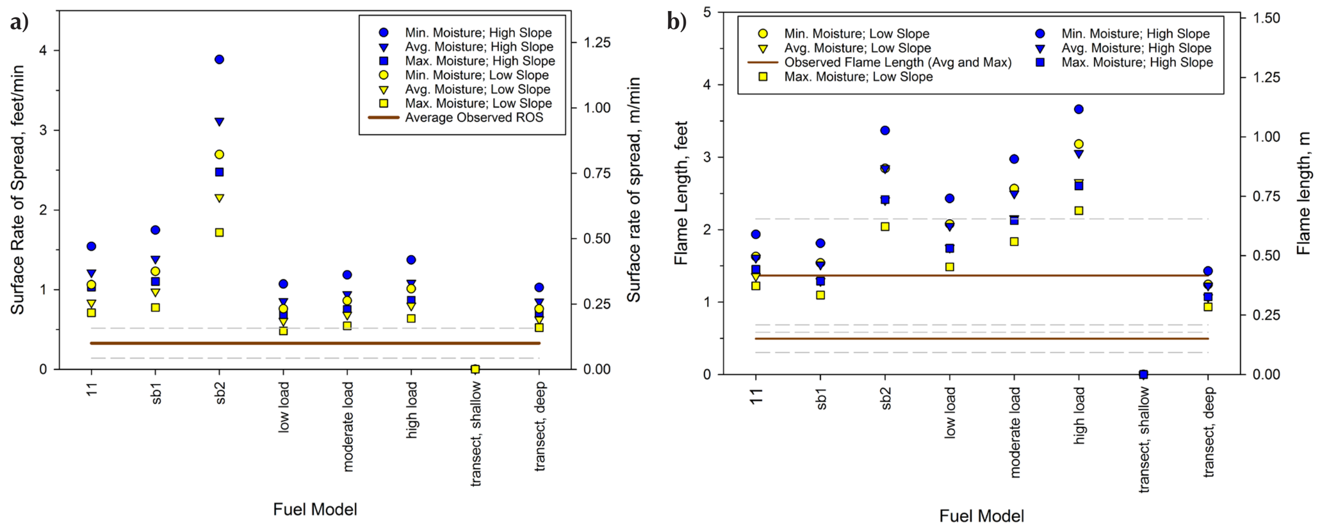

Figure 9—Rate of spread (a) and flame length (b) were modeled using three standard and five custom fuel models. The five custom fuel models were originally developed for fuel beds in CA and SC (see table 4). In all cases, the modeled fire behavior overestimated actual fire behavior. ROS = surface rate of spread

There was a slight relationship between time since mastication and minimum flame length (K_τ = –0.250; P = 0.03).

Fire Behavior Modeling

Rothermel's (1972) fire spread model requires a steady-state fire burning through relatively homogeneous fuels. Therefore, 18 of the 45 experimental burns were used in our fire behavior modeling effort described below. The remaining 27 experimental burns were excluded from the fire behavior modeling because they failed to meet these criteria.

All of the fuel models described previously were compared with results from the 18 fuel beds that could be modeled for fire behavior in this study (fig. 9). Modeled fire behavior was minimal, with rates of spread less than 2 ft/min (0.6 m/min) and flame lengths less than 4 ft (1.2 m). Most estimates of flame length were less than 2.5 ft. (0.8 m). In general, all of the fuel models overestimated both observed rate of spread and minimum flame length, with SB2 generating the highest estimates. The fuel models more accurately modeled observed maximum flame length values.

Within the masticated fuels that could be modeled for fire behavior, several important aspects of burning were observed, none of which can be predicted using current fire behavior models.

1. Once ignited, fuel beds from sites with larger (100-hr and larger) fuel typically burned longer (fig. 10).
2. The smaller (1-hr and 10-hr) fuel facilitated fire spread, while the large fuel continued burning after the flaming front had passed. Once the flames died out, many beds continued to smolder for at least an hour.
3. Rate of spread and flame height tended to increase as the bed burned, which is an indication that the fires did not reach steady-state conditions.
4. Mastication method appeared to have some impact on burning. As stated earlier,

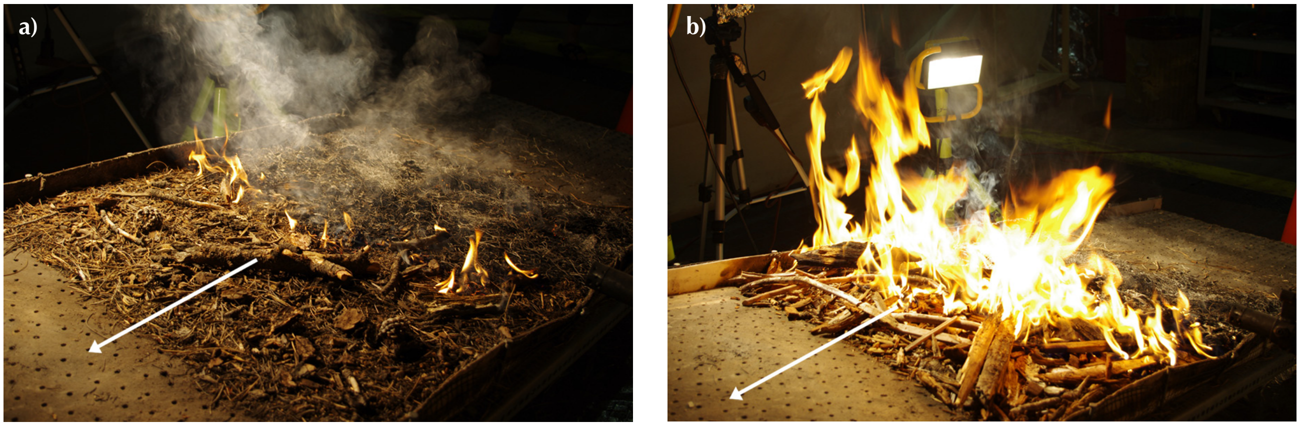

Figure 10—The fuel bed on the left (a) is taken from the Manitou Experimental Forest, Colorado (MEFWS). The fuel bed on the right (b) is taken from the Deception Creek Experimental Forest, northern Idaho (DC1). Mastication was done using a rotating head in both areas. Arrows indicate upslope. These two different fuel beds burned very differently, even though the same masticator head was used.

none of the fuel beds from sites treated with a chipper or mower burned the complete length of the fuel bed, and we were unable to estimate the fire behavior.

5. Often, larger pieces of fuel acted as a barrier to fire spread. Flames burned around or under the larger fuel. These larger fuels tended to light after the flaming front had passed, a result of residual burning and heat generation during the smoldering phase.

Discussion

We did not find a relationship between time since mastication and fire behavior. All of the sites were treated no more than 10 years prior to sampling, and most of the wood was quite sound. Decomposition was not readily apparent and would likely not have been great enough to affect fire behavior. Sites with masticated fuel older than 10 years or in which decomposition was readily apparent (e.g., "punky" or soft, rotted wood) would be expected to show different fire behavior than the ones included in this study.

Mastication method appeared to have some impact on burning. As stated earlier, none of the fuel beds from sites treated with a chipper or mower burned the complete length of the fuel bed, and we were unable to estimate the fire behavior. We hypothesize that the fuel beds that exhibited smoldering fire behavior were too shallow and dense to provide the necessary air flow to ignite the fuel without the assistance of wind. These results are similar to those of Glitzenstein et al. (2006), who measured slow rates of spread and identified large patches of unburned fuel in their prescribed burn experiments in field conditions that were composed of shallow fuel beds. There did not appear to be a clear relationship between mastication type and fire behavior for the sites where a rotating head or horizontal drum head was used. Some of the fuel beds with these mastication methods were able to be used in analysis; others were not.

There are two possible reasons why fuel beds did not burn homogeneously. First, our fuel beds were relatively narrow and the edges of the fuel bed had an effect on the fuel as mentioned previously. Second, the halogen lights affected fire behavior in unpredictable ways. In many cases, the side of the fuel bed with the halogen light burned faster than the side on which the halogen light was removed. There were also experimental burns in which the side without the halogen light burned faster. These edge effects were not consistent among sites, or even within a site, making it difficult to determine exactly what caused the fire behavior observed in these 11 burns.

Given that all of our burns occurred at low moisture levels, we were unable to distinguish between fire behavior at moist and dry sites. However, we were unable to get any of the fuel beds to burn at higher moisture contents, such as those typically found in areas like the Priest River Experimental Forest in northern Idaho (data not shown). Our sites had very little litter to carry the fire or provide the energy necessary to ignite the larger fuels. This limits the utility of our experiments in determining the importance of such factors on observed fire behavior.

With the exception of fuel model SB2, the predicted values of rate of spread and flame length from the fuel models included in this report are reasonably close to observed values of fire behavior in this study (fig. 9). Observed rates of spread in the fairly dry conditions were minimal—at less than 1.0 ft/min (0.3 m/min) and flame lengths less than 3.0 ft (0.9 m). These rates are consistent with those found in other studies of fire behavior in masticated fuel (Glitzenstein et al. 2006; Knapp et al. 2011). The fuel model with the shallow fuel bed as described in Glitzenstein et al. (2006; fig. 9, transect, shallow) modeled a zero rate of spread and flame length for our fuel beds. Glitzenstein et al. (2006) found similar results when developing the fuel model. They hypothesized that the depth of the fuel bed included in the fuel model was too shallow for the Rothermel fire spread model to calculate a rate of spread or flame length. We have included it in figure 9 for completeness, but it has been removed from further discussion. These results, however, support our hypothesis for patchy burning in the shallow fuel beds observed in our laboratory experiments.

Results are also consistent with field measurements from Glitzenstein et al. (2006) and Knapp et al. (2011) who documented low rates of spread and minimal flame lengths. In standard firefighting nomenclature, this indicates that the fire can generally be attacked at the head by firefighters using hand tools (NWCG 2018; Roussopoulos 1974).

Limitations were also evident from these burns that made further analyses difficult. These include the following conditions:

1. All of the fuel beds had similar moisture values because of conditioning (table 3). While this did not allow us to test the full range of fire behavior expected in the field, we were able to test a near worst-case scenario for extremely dry fuel.
2. No live fuels were included in the experimental burns. However, live woody fuel moisture is a required input for two of the custom fuel models. It was assumed to be 150 percent to represent mature foliage in which new growth is nearly complete. Both “low” (12 percent) and “moderate” (21 percent) slopes were used in the calculation of fire behavior.

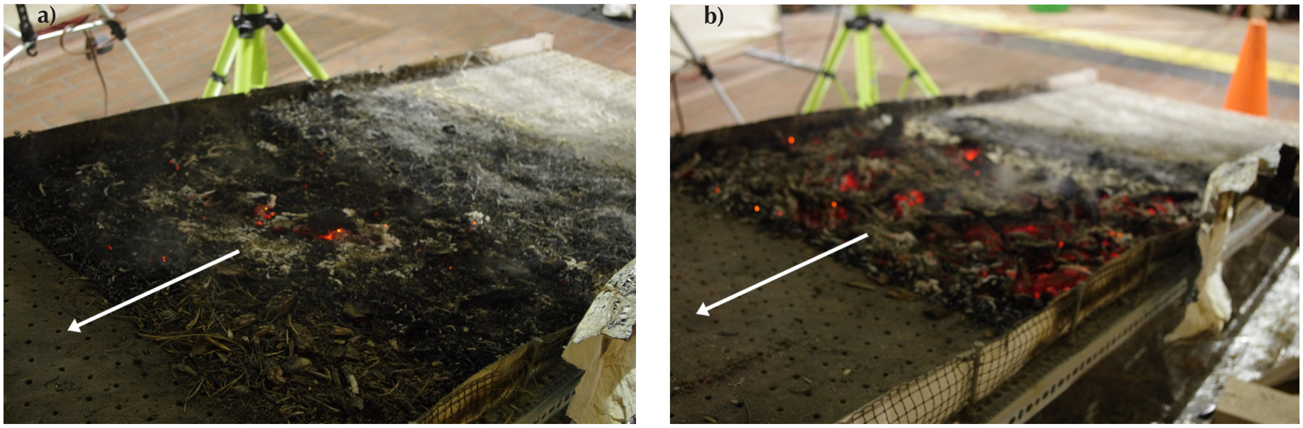

Figure 11—Residual heating and glowing combustion can be an inportant factor when burning these fuels. The fuel bed on the left (a) is taken from the Manitou Experimental Forest, Colorado (MEFWS). The fuel bed on the right (b) is taken from the Deception Creek Experimental Forest, northern Idaho (DC1). Both photos were taken approximately 26 minutes after the experimental fuel beds were ignited and when the last flame had disappeared. Arrows indicate upslope. Many of these burns continued for more than an hour.

3. Wind speed was assumed to be zero.
4. Differences in rate of spread during the burn, while visually apparent, could not be measured in the experimental design.
5. Although fire behavior can be measured and modeled in any direction, many of the burns exhibited only flanking fire, which is much slower than heading fire. We were unable to measure flanking fire rate of spread because the fuel beds were too narrow.
6. Intensity was not measured for the burns in definitive units.
7. We were unable to burn these fuels in a field setting. Therefore, we cannot apply the results from our modeling experiment directly to fire behavior in masticated fuel treatment areas, but rather indirectly with experimental results from more targeted research on field burning of masticated fuel.
8. Residual burning, likely important in these scenarios, cannot be modeled using current fire behavior modeling systems (fig. 11).
9. Several of our experimental burns in heavy fuel, although limited in size, smoldered for more than an hour.
10. We were unable to determine the role of spotting of embers into untreated fuel, particularly under windy conditions.

Facilitated learning analyses (FLAs) specifically written for incidents occurring in masticated fuels document that wind plays an important role in reigniting fires from smoldering embers (residual burning). Given the minimal fire behavior observed in this and other studies, resistance to control as a result of glowing combustion is likely to be of greater concern. Anecdotal evidence and FLAs (e.g., Bass et al. 2012; McDaniel 2013) indicate that masticated fuel burns much longer than other fuel types. Masticated fuel is rarely spread evenly across an area, and pockets of high fuel concentrations have been known to smolder for long periods of time (Kreye et al. 2014). This was also reflected in our experimental burns. When residual heat remains, a change in the weather could cause transition to flaming in surface fuels, leading to issues related to resistance to control (Bass et al. 2012). Thus, there is a need to ensure that a fire is completely out (admittedly a difficult task in heavily masticated fuel) or to establish extended patrols to verify that fires do not reignite and spread.

While spotting models have been developed for torching trees, wind-driven surface fires, burning piles, and active crown fire (Albini 1979, 1981, 1983; Albini et al. 2012), they cannot be used for masticated fuel because of the unique nature of these fuel beds. Currently, no model can adequately estimate the spotting distance of an ember from masticated fuel. Therefore, managers should consider if there is a need for a buffer between masticated fuels and the treatment unit boundary. This buffer would be free of masticated fuels and treated if necessary to minimize potential rate of spread and flame length (Bass et al. 2012).

Several authors have described a need for custom fuel models in masticated fuels (e.g., Kreye et al. 2014), but there are many uncertainties when modeling fire behavior in these novel fuel beds. When Rothermel's fire spread model is used, the assumptions and limitations are well-documented (e.g., Andrews 2014; Rothermel 1972, 1983; Rothermel and Rinehart 1983): the fuel bed is assumed to be homogeneous, fine fuel is considered the primary carrier of fire, and fire behavior is calculated for a heading fire (in direction of maximum spread). We were unable to create custom fuel models for our burns because (1) there were no observational data from the field for comparison to results from any fuel models we would create, (2) wind was not considered during the experiments, and (3) we were unable to measure the observed flanking fire behavior or associate it with forward spread predictions from the model. In addition, other factors must also be considered in the modeling effort. Masticated fuel is unique in that there can be a large component of woody fuel in all dead fuel classes and the fuel load may be dominated by larger fuel. Fuel bed depth can also be heavily influenced by the machine used for mastication as can the particle sizes and shapes (Keane et al. 2017). These factors make it difficult to calculate the components of a custom fuel model using the data from our experimental burns.

Conclusion

This study was designed to characterize fire behavior in masticated fuels at sites in these four States through experimental burns and fire behavior modeling. Overall, there was great variety in the observed fire behavior, and age of the fuel did not appear to play a role in fire behavior. The type of mastication and resulting fuel bed depth did play a role. Some fuel beds, such as those that were chipped or mowed, failed to burn completely. These beds tended to have more densely packed fuel or shallow fuel beds. Other beds exhibited flanking fire behavior caused by edge effects from the fuel bed or from large pieces of fuel restricting fire spread. Still other fuel beds burned fairly evenly and consistently across the entire bed.

Given the experimental design, we were unable to create custom fuel models to potentially improve fire behavior estimates. With the minimal fire behavior observed in this study, uncertainties in the fire behavior models themselves (Byram 1959;

Rothermel 1972) could account for differences between the observed and predicted fire behavior (Rothermel and Rinehart 1983).

Even though the results from this study appear to contradict claims that fire in masticated fuels is difficult to manage, these results are limited to fire behavior of a flaming fire front in a controlled setting. The fuel beds in this study also came from sites with little litter or grass to carry a fire. Posttreatment regeneration of grasses and shrubs may also change the surface fuels, potentially increasing fire behavior in masticated fuel beds.

Concerns regarding burning masticated fuel may or may not exist during initial fire spread. Residual burning makes containment and mop up difficult, particularly in areas with deep pockets of masticated fuel, such as those created by rotating or horizontal head drums. Residual burning and spotting across the containment line have been documented in many wild and prescribed fires in these fuel types. These issues, particularly under windy conditions, lead to very different fire behavior both within and outside the treated area. Wind contributes to spotting, causing embers to land in the untreated fuel outside the treatment zone. Unfortunately, no model currently exists to estimate spotting potential for masticated fuel. It is important, therefore, to model not only the fire behavior within the treatment area, but also the fire behavior in surrounding vegetation.

Glitzenstein et al. (2006) wrote of their masticated materials, "Practically speaking, all the fire behavior predictions … were close enough to measured values to satisfy a prescribed burner or wildland firefighter," (p. 25). Similarly, none of the observed or modeled fire behavior in this study would seem to indicate changes to fire management operations. With this in mind, the SB1 fuel model effectively approximated fire behavior in our experimental fuel beds. However, rate of spread and flame length at the flaming front are arguably not the most important considerations for land managers during a wildland fire in masticated fuels. Canopies at masticated sites are usually opened to reduce the potential for crown fire. This characteristic alone reduces the potential for wildfire severity, transition to crown fire, and firefighter injury (Battaglia et al. 2010; Kreye and Kobziar 2015; Reiner et al. 2009; Schwilk et al. 2009).

There is still abundant research needed for these novel fuel beds. Future research should focus on the length of time pockets of fuel are capable of burning to assist managers in prioritizing patrol and mop up. Spotting models should be developed, and these models could well depend on the type of masticator used to treat the fuels. Laboratory models need to be verified in the field to be of more use to managers. Further, models need to be developed for rate of spread for a flanking fire in addition to rate of spread for a heading fire because both behaviors are important in this type of fuel. Research is also needed regarding the increased loading of surface fuels that burn for long periods of time and that could cause long-term heating of soil or plant parts (such as roots and stems), affecting a masticated site's ability to regenerate after a fire.

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